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FLAME RETARDANT TEXTILES FOR ELECTRIC ARC FLASH HAZARDS: A REVIEW

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ABSTRACT

Research in textile materials with flame retardant properties for protective clothing is part of a macro-trend of professional protective uniforms development. In this scenario, it is observed a high demand for workers exposed to risks of electrical hazards caused by electric arcs or flash fire, due to lethality or brutal consequences of it. Therefore, once its scenario shows an extreme risk, the material used for protective clothing must attend some rigid criteria. That way, uniform so-called FR (flame or fire retardant) is capable of making ignition difficult and slowing down the flame spreading, reducing the risk of more severe burn injuries. This article overviews the most used FR textile materials in personal protection equipment (PPE) that attends voltaic arc protection, current research in textile materials with anti-flame and arc-flash protection, and investigates the new tendencies in research of materials, methodologies and techniques in FR segment

KEYWORDS: Fire Resistance, Voltaic Arc, Electric Hazards, Protection Textiles & Personal Protection Equipment

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Original Article

INTRODUCTION

As a way to guarantee safety and protection for workers that are constantly exposed to burning risks and to extreme/hostile conditions, some procedures are mandatory. As an example, the use of protective uniform is capable of protecting or, at least, considerably minimizing possible damages from the industrial activity. According to data report published by International Labor Organization (ILO, 2018), every 15 seconds a worker dies due to an accident or a work related disease. In other words, 6,300 deaths per day, which leads to a sum of 2.3 million death and 300 million injured workers per year. In 2020, the Statistical Yearbook of Electrical Accidents from Brazilian Association for Awareness of the Dangers of Electricity(ABRACOPEL 2021), through historical data between 2013 and 2020, workers from electrical segment are the main victims of injuries by electrical shock. Only in 2020,Brazil counted 237 deaths in electric network distribution segment (ABRACOPEL 2021).

Activities that involve electrical systems in general will expose operator to risks and make it necessary to follow safety standards, whether about proper training, correct handling, appropriate Personal Protective Equipment (PPE), etc. Among the risks in this nature of work, the electric arc is the most harmful and dangerous. An arc failure may cause serious accidents, such as thermal impact, pressure wave, particle projection, electrical and toxic impact, as well as lethal burns. In addition, serious damage to equipment, electrical panels and installations may also be listed(Bulwark FR 2016; Kanokbannakorn et al. 2016; Kumpulainen et al. 2014). Electric arcs occur when there is a large electrical current passing at high speed through a material that is not conductive, such as air. This is usually due to short circuits and electrical failures. This event is usually rapid and chaotic, and it

can quickly extinguish or ignite. Thus, given its nature, it is difficult to specify the properties of the generated arcs, such as the value of their impedance, for example. However, it is known that they reach very high temperatures, above 20,000°C at the point of origin of the arc. Furthermore, there is a great risk of explosion due to the pressure generated during the formation of these arcs(Senger and Queiroz 2012; Shelke and Wen 2021).

In the last years, flame or fire retardant (FR) and voltaic arc protective garments have proved to be highly efficient to ensure the safety of workers that are constantly exposed to thermoelectric risks, and several reports of such data can be found in the literature (Deng et al. 2021; International Labour Organization (ILO) 2019; Kanokbannakorn et al. 2016; Kumpulainen et al. 2014; NFPA 70E 2020; Rômulo and Senger 2012; Senger and Queiroz 2012; Udayraj et al. 2016). The Electrical Safety Foundation International (ESFI), using data from U.S. Bureau of Labor Statistics in 2020, reported that fatal accidents caused by electrical hazards have been reducing its occurrence since 2003 (Figure 1). Also according to the ESFI (2020), the graph of non-fatal accidents from 1992 to 2020 (Figure 2) indicates a great decrease, although the numbers are still high, reinforcing the fact that research and development of safety equipment is essential for keeping this trend down.

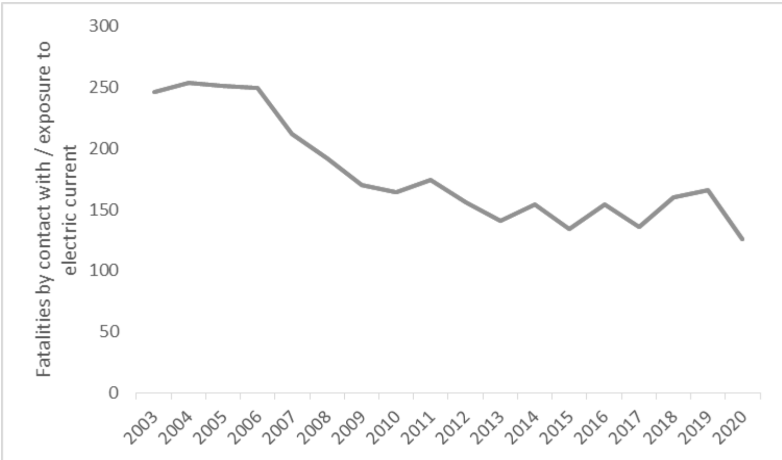

Figure 1: Fatalities Caused by Contact with/Exposure to Electric current in USA, during 2003 to 2020. Adapted from: (ESFI, 2020).

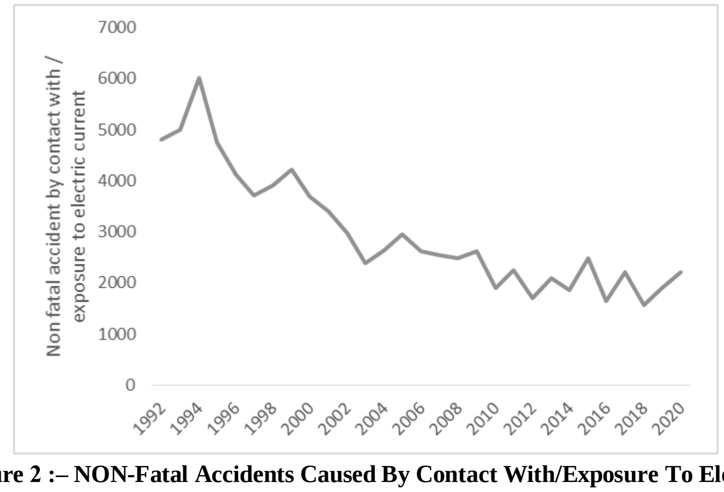

Figure 2 :– NON-Fatal Accidents Caused By Contact With/Exposure To Electric Current in USA, During 2003 to 2020. Adapted from: (Esfi, 2020).

It has been proved, through showed data above, the importance of investment and research in protection segment. The importance of been aware of this data and results are great for the successful development and increase of segment. In industry or home daily, humans are constantly being exposed to electric hazards and efficient PPE helps to improve quality life. As a protection segment of great importance for safety, materials must attend high criteria and it is highly recommended a recent review. According to literature, the most recent document about a review of flash hazards protection textiles is from 2013 (S. Li et al. 2013).However, there are many research in literature that keeps achieving new fire resistance level after this, with research about application of new materials in FR segment, green-based technologies and sources, and even new PPE techniques. The main goal of this paper is to update the lasts reviews in segment by correlating the fibers used in fire resistance textile segment; determine which of them can guarantee arc voltaic protection and update what are the new trends in FR material, technologies and methodologies.

2. FIRE RESISTANT TEXTILE MATERIALS

Fire resistant (FR) textile materials can interfere in two or more requirement of combustion process (heat, fuel or oxygen), leading to a high heat and flame resistance. Its feature can be measure by the temperature of ignition (Tc) or temperature of pyrolysis (Td), greater the temperature of flame, more flammable is the fiber (Norouzi et al. 2015; Price and Horrocks 2013). Other parameter used to measure the fiber/yarn/fabric flammability is the Limiting Oxygen Index (LOI).LOI is a laboratorial test that measures the relative flammability of materials and its standardized in NFT 51-071 or ASTM D2863. The test determine the minimum of oxygen concentration [O_2] (in percents) of a O_2/N_2 mixture is needed to either maintain a 3 minutes flame or the burning of 5 cm of sample's length (ABNT NBR IEC 60695-2-11 2016; ASTM D2863-00 2017; EN 60695-2-11 2014). Values lower than 21% (natural oxygen contained in air) are highly flammable; LOI values around 21 – 25% are moderately flammable and, usually, textiles with LOI values higher than 25% are approved in many national and international standard tests for flame retardant textiles (Khan 2019; Kundu, Gangireddy, et al. 2020; Laoutid et al. 2009; Norouzi et al. 2015; Price and Horrocks 2013).This property can be achieved by two main processes: by using inherent FR materials or adding to textiles' surface a chemical treatment(Didane et al. 2012; H. Gu 2009; Gurusamy Pandian and Ashifa 2020; Hamouda 2018; Kundu, Gangireddy, et al. 2020; Martini et al. 2010; McPartlin et al. 2021; Trombini 2004; Wan et al. 2020).

Some synthetic fibers, filaments and yarns that present FR properties are usually those thermoset aromatic fibers, or thermoplastic ones with addition of FR fillers by extrusion or in-situ polymerization, such as phosphorous and non-halogenated based chemicals, among others(Gurusamy Pandian and Ashifa 2020; Khan 2019; Kundu, Li, et al. 2020; Liang et al. 2020). There are commonly FR materials used in protection garment confection, such as aramid fibers, with is classified into two types - meta and para-aramids; viscose fibers; polyamide fibers; modacrylic; polyethylene terephtalate (PET) fibers; oxidised poly(acrylonitrile) fiber (OPAN) or preoxidized acrylonitrile fiber (PREOX); polybenzimidazole (PBI); poly(p-phenylene-2,6-benzobisoxazole) fiber (PBO); phenolformaldehyde fibers, or Novoloid (commercial known as Kynol®) and Vectran®.

For other side, there are fiber materials that have FR properties but they are not applied in textile segment. However, considering their performance and flame/fire/heat resistance, those materials should be highlighted and posteriorly investigated in protection garment segment. One example is polyether ether ketone (PEEK), with one of the main properties of PEEK is its high resistance in extreme conditions (thermal, chemical, mechanical and abrasion). It is very used as FR material in many areas, such as: aerospace, automotive and medical(Bourbigot and Flambard 2002;

Hufenus et al. 2020; Trivedi and Rachchh 2022).Other significant FR polymer is poly(phenylene sulfide) (PPS), with a sulphur-containing fiber, named as Sulfar by Federal Trade Commission, once its chains structures are unique and does not apply in polymer classes. PPS main applications includes chemical resistant filters, reinforcing material, and insulators (Bourbigot and Flambard 2002; Fei 2017; Hufenus et al. 2020).

The wool fiber is also a inherent material, from natural proteic fiber that, beyond increasing comfort, guarantees a low inherent flame resistance with slow burn and LOI of 25% (Flambard et al. 2002; Weil and Levchik 2008). Cotton in another natural fiber widely used in textile segment, including fire protection material, despite its low LOI value (18%) and facilitate to ignite, due to the possibilities of FR surface treatment (Chavali et al. 2020; Grancaric et al. 2017; Wan et al. 2020; S. Wang et al. 2021). Table 1 correlates the principal properties of materials.

Table 1: Most Common Materials Used In Fire Protection Textile Segment And Its Properties

Fiber Material	LOI(%)	Fire resistance	Comfort	Reference
Cotton (treated)	18 - 54	--	++	(Chavali et al. 2020; Qi et al. 2022; Z. Zhang et al. 2019)
Wool	25	+	++	(Horrocks 2016)
Meta aramid	29-30	++	-	(Amesimeku et al. 2021; Price and Horrocks 2013; K. Wu et al. 2020; Cong Zhang et al. 2020)
Para aramid	29	+	-	(Amesimeku et al. 2021; Price and Horrocks 2013; K. Wu et al. 2020)
Viscose	18,9	--	++	(Graupner et al. 2020; Liang et al. 2020; Liu et al. 2020; Ranganathan et al. 2016)
Polyamide	21-24	+		(Y. Y. Li et al. 2017; Price and Horrocks 2013)
Modacrylic	29-30	++	++	(Kim and Kim 2018; Penthala and Son 2021; Price and Horrocks 2013; Tanaka et al. 2015)
PET	21	-	+	(Didane et al. 2012; Fei 2017; Hufenus et al. 2020; Tao et al. 2021; Chenxi Zhang et al. 2021)
OPAN	55	+		(Bourbigot and Flambard 2002; Martini et al. 2010; Terra et al. 2021)
PBI	41	++	+	(Davis et al. 2010; Fei 2017; Houshyar et al. 2016; Menczel 2020)
PBO	68	++		(IMATTEC 2022a; Seely et al. 2004; Sharma et al. 2019; Toboyo 2022)
Novoloid	30-40	++	+	(Duquesne and Bourbigot 2010; Gooch 2011; Horrocks 2016)
Vectran®	30	+	+	(IMATTEC 2022b; Komorek et al. 2021)
PEEK	35	++	-	(Bourbigot and Flambard 2002; Hufenus et al. 2020; Trivedi and Rachchh 2022)
PPS	40	++	-	(Bourbigot and Flambard 2002; Fei 2017; Hufenus et al. 2020)

Once, inherent FR materials are expensive, other alternative is to apply directly in the surface of the fabric a chemical treatment, which composition can be constituted by fire retardant materials.

A FR finisher is defined as a chemical product that, when applied in a combustive material, leads to a reduction in its ignition and flame propagation by isolating the flammable gases generated during combustive process (such as pyrogen, oxygen and other flammable gases) (Gurusamy Pandian and Ashifa 2020; Nie et al. 2021). Besides being extensively

applied, FR materials containing halogenated compounds (as additives or inherently in its structure) are highly dangerous to environment and human health. Among their biggest risks, can be mentioned: toxicological effects, contamination, potential disruption of neurological and organ function and release of toxic volatiles when exposed to heat or flame (Cheng et al. 2020; J. Gu et al. 2021; McPartlin et al. 2021; Chenxi Zhang et al. 2021). Non-halogenated FR materials are a high efficiency and eco-friendly alternative (McPartlin et al. 2021; X. Zhang et al. 2021). They usually have in their structure phosphorous based compounds (Qi et al. 2022; Wan et al. 2020; W. Wu and Yang 2007; F. Zhang et al. 2018), but is also observed in literature, silicon (Cheng et al. 2020), nitrogen(Luo et al. 2022) and sulfur (Jin et al. 2021).Phosphorous-based compounds as a flame retardant acts by transforming phosphorus into phosphoric acid, during thermal decomposition of treated material. This acid is non-volatile and reacts with the decomposition macromolecules of textile material by esterification, leading to dehydration and eventually to promotion of char residue formation(Chen et al. 2022; S. Wang et al. 2021). FR finishing treatment is mainly used in cotton fabrics, the natural fiber most used in textile industry, due to its previously mentioned properties and its low cost (Feng et al. 2017; Jang et al. 2018; Luo et al. 2022; Wan et al. 2020).

Despite the fire and heat protection that material must have, not all fire retardant materials can be applied as a voltaic arc protection material. Once injuries caused by electric arc exposure are way more severe than flame exposure, industries should attend more rigid criteria.

3. VOLTAIC ARC MATERIALS CRITERIA

When a voltaic arc occurs, it generates light and a high thermal radiation that can achieve over 35,000°C. Beyond that, arc may cause burns, hearing loss, eye injuries, skin damage from blasts of molten metal or flying particles, lung damage, blast injuries, third degree burns or even death. To avoid those injuries, a proper material should be used in the garment confection, as a measure to protect the worker(Guo et al. 2022; Henrique and Brotto 2021; X. Li et al. 2021).

A series of precautions should be taken when it is intended to work with electrical hazards. To categorize these materials and ensure the protection factor, some criteria were defined. Regulaments around the world intend to establish some safe criteria to protect and preserve worker's integrity, such as National Fire Protection Association 70E-Standard for Electrical Safety in the Workplace – NFPA 70E (NFPA 70E 2020); Institute of Electrical and Electronic Engineers – IEEE 1584 Standards (Doan et al. 2010), and Norma Regulamentadora de Número 10 (NR-10 – Regulatory Standard, in english), from Brazil (Ministério do Trabalho 2004).

It is important to acknowledge the correct known risks and exposures that each activity may cause, to consequently being able to select the textile materials that might be applied in PPEs and techniques to manufacturing them. There are five risk categories and each one of these is correlated to an incident energy value (cal/cm²) and the minimum ATPV (Arc Thermal Protection Value) required by PPE. ATPV, according to American Society for Testing and Materials (ASTM) F1959 standard, consists of a value in calories per square centimeter of the protection provided by the fabric to the thermal effect from an electric arc. It serves as an indicator for measuring the performance of FR fabric for application in each industrial activity (ASTM F1959 2017; Bottaro and Eichinger 2018; NFPA 70E 2020).To classify the labor hazard according to risk category, simulations of task environment must be made to determine what is the potential arc exposure. The most extreme scenario in incident energy exposure must be considered (Doan et al. 2010).

Here are many ways to keep the workers in more safe conditions during their job. In addition to inspection, routine maintenance, certification of equipment used and qualified team, in order to guarantee the worker a risk-free

environment, it is important to pay attention to the use of correct personal protective equipment (PPE).This PPE should be tested in order to attest its performance. Table 2 correlates the risk category, the minimum incident energy value that equipment must support to avoid a second degree burn and the PPE required(Doan et al. 2010; NFPA 70E 2020).

Table 2: PPEs And Its Respectively Risk Category(Doan et al. 2010; NFPA 70E 2020)

Risk Category	Incident Energy Value (cal/cm²)	Protection Garment	Number of Layers*
0	Less than 4	Protective clothing, untreated natural fiber, with a minimum weight of 152 g/cm²; shirts (long sleeves); pants (long); safety glasses; hearing protection (insertion model in the ear canal); leather gloves when needed	1
1	Higher than 4	Arc-rated long-sleeve shirt and pants or arc-rared coveralls; arc resistant face shield or arc resistant executioner hood; helmet; safety glasses; hearing protection (insertion model in the ear canal); leather gloves; leather safety shoe when needed	1
2	Higher than 8	Arc-rated long-sleeve shirt and pants or arc-rared coveralls; arc-resistant face shield or arc-resistant executioner hood and arc-resistant balaclava; arc resistant jacket, tracksuit, waterproof clothing or helmet lining when necessary; helmet; safety glasses; hearing protection (insertion model in the ear canal); leather gloves; leather safety shoe when needed	2
3	Higher than 25	Arc-resistant long-sleeve shirt; long bow resistant trousers, when required; arc resistant coveralls, when required; arc resistant jacket, when required; arc-resistant hangman hood; arc resistant gloves; arc resistant jacket, tracksuit, waterproof clothing or helmet lining when necessary; helmet; safety glasses; hearing protection (insertion model in the ear canal); leather safety shoe when needed	3
4	Higher than 40	Arc-resistant long-sleeve shirt; long bow resistant pants, when required; arc resistant coveralls, when required; arc resistant jacket, when required; arc-resistant hangman hood; arc resistant gloves; arc resistant jacket, tracksuit, waterproof clothing or helmet lining when necessary; helmet, safety glasses, hearing protection (ear canal insertion model), leather safety shoe when needed.	4

*Layers of fabric, which can be garment with lining and/or pieces of clothes overlaid.

4. PERSONAL PROTECTIVE EQUIPMENT (PPE)

Even though ATPV value is the most important criteria to determine the applicability against electric hazards, studies have been showed that clothing comfort is one of the major concerns of garment manufacturers(Das and Alagirusamy 2011; Kilinc-Balci 2011; McLoughlin and Paul 2017). The concept of confort is relative and may vary according to the user’s opinion. However, the main parameters are: fit, touch and tactile properties (if friction forces are not too high or if fabric is soft, for example), flexibility, surface roughness, low weight, allergies or skin reactions, thermo-physiological properties (such as sweat vapour dissipation), drape and aesthetic (Das and Alagirusamy 2011; Kilinc-Balci 2011; McLoughlin and Paul 2017; Scott 2009; Udayraj et al. 2016).

According to Silva-Santos and co-workers (2017), the use of natural FR materials, such as cotton and wool, is massively investigated due to their softness and comfort, when compared with synthetic fibers. Those fibers result in lighter and breathable fabric, resulting in very operational and functional design(Silva-Santos et al. 2017). A 100% natural

fiber, however, is not heat and flame resistant enough to be qualified in arc resistance segment. For those cases, a fabric based on natural-synthetic fibers is possible. There are many commercial fabrics meeting these characteristics, for example Protal 5®, Indura® 867 and Titânio®. Besides being a synthetic fiber, modaclylic is a fiber known by its fire-proofing and comfort properties. Viscose fibers also give comfort to garments. Those materials, on other hand, are more expensive than natural fibers (Kim and Kim 2018).Another factor that influences clothing comfort is the knitting. According to McLoughlin and Paul (2017), knitted structures remove liquid sweat and provide tactile and sensorial comfort(McLoughlin and Paul 2017).

5. NEW TENDENCIES

New inherent fibers and FR finishing treatment are extensively investigated in literature. The following studies indicated new materials, methodologies and technologies that resulted in final products with potential to, eventually, achieve the criteria to arc voltaic protection.

Technologies and Methodologies

Ling and Guo (2020) used a solvent-free methodology to treat cotton fabric surface with an FR finishing of hyperbranched polyester. The finishing contained reactive groups that can form strong covalent bonds with cellulose, which resulted in an increase in flame retardancy, cotton resistance and LOI value (reaching up to 42% and 29%, even after 50 laundering cycles) (Ling and Guo 2020).

Zhai and coworkers investigated the application of thin layers of Al/SiO_2 films, by magnetron sputtering, in aramid fabric's surface. The finishing is an alternative to improve effectiveness of protective garments by increasing its reflectivity and, thus, reducing the absorbed temperature (Zhai et al. 2015).

Abu Elella and coworkers treated the surface of a cotton/polyester textile with polypyrrole and silver nitrate ($AgNO_3$) via vapor phase polymerization (VPP). First, textile samples were treated with silver nitrate and then submitted to vapor polymerization with pyrrole monomers. Treated samples achieved good electrical, mechanical, thermal and fire resistance. It was also observed an increase of 46% in flame retardation after treatment. Beyond that, the methodology increased the wash resistance of $AgNO_3$ nanoparticles, where polypyrrole layer acted as a stabilizer (Abu Elella et al. 2021).

Wang and coworkers modified activated carbon granules with Si, in order to obtain a volatile organic compound with FR properties. Samples were submitted to toluene adsorption-desorption experiments and authors observed that the efficiency remained at nearly 80%, even after five cycles. This performance indicated great potential for industrial applications (X. Wang et al. 2021).

Shaid, Bhuiyan and Wang developed an aerogel-nonwoven protective fabric to act as thermal protective in a multilayer clothing. The aerogel obtained was more flexible and less dusty than commercial reference and presented similar thermal resistance (Shaid et al. 2021).

Zhang and coworkers synthesized a hydroxyl-containing cyclic phosphoramide DPHP (2,2-dimethyl-1,3-propanediol-(2′-hydroxyethyl)phosphoramidate) as flame retardant to later apply in PET fabric. The goal was to improve fire and heat resistance of fabric. It was observed an increase of 27,6% in LOI (when compared to neat PET), good performance in vertical flammability and a non-dripping behavior. When investigating char residues, authors witnessed

many worm-like particles, which authors correlated with the good heat insulation, confirming the great flame retardancy and non-dripping burning effects (Chenxi Zhang et al. 2021).

Fang and coworkers developed a conductive, flame retardant and anti-dropping PET fabric, by using PA@PANI (polyaniline and phytic acid as dopant). Authors believed that multifunctional textiles are an interesting field that should be explored and increased in traditional applications, once they can achieve performances that cannot be reached by single-functional fabrics. Those textiles have advantages in some special fields. Authors used as example the firefighting suits with conductive and flame retardant: they say those garments can not only protect the lives of firefighters in the fire scene but also monitor the movement status of firefighters through the electrical signals reacted by the firefighting suits. Textile material obtained in this paper presented a great fire resistance, LOI of 33,5% and complete disappearance of melt-drop effect (Fang et al. 2022).

Atmospheric Plasma

Thi and coworkers treated cotton fabric surface with atmospheric-pressure dieletric barrier discharge plasma to posteriorly treat with FR chemical. Plasma treatment step resulted in a significant reduction in temperature and time of FR treatment step, which lead to a reduction in mechanical strength loss in post treatment cotton fabric (Thi et al. 2020).

Inherent Fibers

Kynol® fiber for years was known as being relativity weak, due to its cross-linked structure (Horrocks 2016), which resulted in Kynol being used only in nonwoven fabrics. However, it is now possible to find in current market some yarns made from 100% Kynol® fiber, indicating the possibility of a new range of applications for those great-performance material.

Green FR Chemicals

Sustainable FR finishing, obtained from natural resources, such as biomass (Pan et al. 2017; Rahman et al. 2021; Z. Zhang et al. 2019), animal (Laufer et al. 2012; Vahabi et al. 2021), plants (Carosio et al. 2015; Feng et al. 2017; Liao et al. 2021)or microbial are being extensively studied and have been showed great performance. Those natural materials act as FR due to the presence of abundant casein (phosphorus-containing molecule) and hydrophobins (sulfur and nitrogen-containing molecules) in their chains promotes cellulose char formation when ignited(Cheng et al. 2020; Meng et al. 2020; Muktha and Keerthi Gowda 2017; Vahabi et al. 2021).

Suryaprabha and Sthuraman (2020) investigated the effect of a DNA-based FR finishing in cotton textile. They observed that the finishing promoted a great increase in thermal stability, a decrease in the spread speed of fire and, beyond that, a super hydrophobic character. The surface treatment also achieves great chemical and mechanical stability (Suryaprabha and Sethuraman 2020).

Zhang and coworkers produce natural grown fungi fiber with FR properties. The authors enriched fungi's nutrition with Si source and observed that it was absorbed and converted into part of the hyphal structure. This strategy leads to an improvement in thermal stability and fire resistance (X. Zhang et al. 2021).

The work of Cheng (2020) consisted in an environmentally flame retardant coating based on phytic acid doped silica sol. The treated samples degraded in lower temperatures, but presented higher thermal stability at higher temperatures. Beyond that, treated samples released less smoke, as a barrier effect and insulating behavior of phosphorus-

containing char residues (Cheng et al. 2020).

A great on spot area of green FR is graphene-based materials, due to their unique structure and properties. Graphene has excellent mechanical strength, high specific surface area and has strong interaction with polymeric chains (Trivedi and Rachchh 2022). Chavali and co-workers (2020) developed functionalized graphene oxide (FGO) nanocomposites-based intumescent flame-retardant coating for cotton fabric. It showed superior flame-retardancy properties, among the green apple (flame exposure ~1500°C) (Chavali et al. 2020). Another work, developed by Jang and co-workers (2018), treated cotton fabric with graphene multilayer nanocoating. TGA, cone calorimetry and VFT results indicated that the treatment increased tendency of incombustibility (Jang et al. 2018).

ε-Caprolactam-based Polyamid 6 Fibers

Nowadays, in literature, due to environmental pollution issues and limited petroleum resources, renewable alternatives for obtaining polyamide are being investigated. Vasilijevic and coworkers (2019) developed a PA6 fibers through ε-caprolactam monomer and fire retardant. The obtained yarns demonstrated a good indicative for flame resistance applications (Jelena Vasiljević et al. 2019).

In the subsequent year, the team developed ε-caprolactam-based PA6/multilayer graphene nanoplatelet composite textile filaments, in order to investigate composite’s behavior. Graphene lead polymer to an increase in crystallization temperature and crystallization; increased thermal stability and graphene’s anti-dripping properties indicated an effective support for gas-phase active flame retardants, leading to an anti-dripping self-extinguishing properties for PA6 textile materials(Jelenade Vasiljević et al. 2020). Recently, Kovács, Pomázi and Toldy (2021) prepared ε-caprolactam-based PA6 in situ and investigated several fire retardants that are promising to increase PA6 fire resistance (Kovács et al. 2021). However, this research area is still very recent and many investigations should be done before applicable results being observed.

6. FINAL CONSIDERATIONS

- The development of protective textile materials is a growing area, with constant innovation and a good variety of applied materials, techniques and methodologies. What allows this growth and what generates the positive results showed along this paper is the possibility of investment in many research fields, ranging from the search of new materials to the study of confort and usability improvements.
- There are an increasing number of new segments emerging, with solutions and facilitations. Market trends suggest great opportunities for nanotechnology, plasma treatment and new fibers with high LOI value in the FR clothing market. Latest years have been heavily focused in green-based FR technology in literature, since plants until DNA-based precursors.
- Several works demonstrate that those new materials, technologies and techniques have a great potential and might be able to attend voltaic arc criteria. It is undeniable the positive contribution of textile materials in FR garment segment in society and both production and research should be encouraged.

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